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Joint US/Russia TU-144 Engine Ground Tests

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Abstract

Two engine research experiments were recently completed in Moscow, Russia using an engine from the Tu-144 supersonic transport airplane. This was a joint project between the United States and Russia. Personnel from the NASA Lewis Research Center, General Electric Aircraft Engines, Pratt & Whitney, the Tupolev Design Bureau, and IBP Aircraft LTD worked together as a team to overcome the many technical and cultural challenges. The objective was to obtain large scale inlet data that could be used in the development of a supersonic inlet system for a future High Speed Civil Transport (HSCT). The first experiment studied the impact of typical inlet structures that have trailing edges in close proximity to the inlet/engine interface plane on the flow characteristics at that plane The inlet structure simulated the subsonic diffuser of a supersonic inlet using a bifurcated splitter design. The centerbody maximum diameter was designed to permit choking and slightly supercritical operation. The second experiment measured the reflective characteristics of the engine face to incoming perturbations of pressure amplitude. The basic test rig from the first experiment was used with a longer spacer equipped with fast actuated doors. All the objectives set forth at the beginning of the project were met.

Background

As part of the National Aeronautics and Space Administration (NASA) High Speed Research (HSR) Program, a United States (US) Government / Industry team and the Tupolev Design Bureau will be using a Russian Tu-144 supersonic transport as a flying testbed for conducting research on high-speed enabling technologies. NASA considered using the Tu-144 in September of 1993 as a result of US-Russia joint discussions on aeronautics. Subsequent studies by NASA, US Industry and Tupolev engineers concluded that because of its size, performance characteristics and availability, the aircraft would be an effective and economical flying testbed. The program fit nicely with American foreign policy and was included as part of an agreement on economic and technological cooperation signed by US Vice President Albert Gore and Russian Prime Minister Viktor Chernomyrdin.

In a meeting in May of 1994 the US suggested the addition of two experiments to study the airflow characteristics in the engine inlet. Tupolev suggested to the US the use of their Engine Test Complex at the Zhukovsky Air Base and the RD36-51A engine which had been previously used on the Tu-144 aircraft. The US accepted the proposal and two new experiments were added. Experiment 3.1 was titled "Engine Operation Behind Close-Coupled Inlet Structures" and 3.2 was titled "Engine Face Reflection Properties."

Another meeting took place in Moscow in September of 1994. During that meeting, the US side had the opportunity to visit the Engine Test Complex and become familiar with the engine, the test rig and its capabilities. It was decided then that the proposed test complex met all the requirements for the ground experiments. Also during that meeting, the inlet test rig concept for both experiments was agreed upon as well as each side's responsibilities.

Subsequent meetings were held in Moscow during the months of May and September of 1995. The purpose of those meetings was to conduct detailed reviews of the aerodynamic and mechanical designs of the test rig. At the September 1995 meeting an

agreement was reached on the feasibility of the mechanical design and a go ahead was given to start the release of the fabrication drawings and the fabrication of the test rig components.

This paper describes the experiments conducted, the technical challenges associated with conducting these kind of tests on foreign soil, and presents preliminary test results.

Objectives

Experiment 3.1

The objective of the Engine Operation Behind Close-Coupled Structures experiment, or Experiment 3.1, was to provide criteria on the impact of the inlet support strut proximity to the inlet/engine interface plane as measured by changes in total pressure distortion. The inlet structure used in the experiments simulated the subsonic diffuser of a supersonic inlet structure that has trailing edges in close proximity to the inlet/engine interface plane. The centerbody maximum diameter was designed to permit choking and slightly supercritical operation.

During the experiment the distance between the trailing edge of the support struts (splitter) and the inlet/engine interface plane was changed using the 1/3 engine diameter (De), 2/3 De, and 1 De ducts shown in Figure 1. The optimum distance will be that which provides adequate open duct area for mixing of the strut wakes before entering the engine. The other variables in the experiment were the engine corrected flow and the use of flow fences and distortion screens. The flow fences were used to generate a boundary layer similar to that found in 2-dimensional bifurcated inlets. Both steady state and dynamic pressure data were obtained during this experiment.

Experiment 3.2

The objective of the Engine Face Reflection Properties experiment, or Experiment 3.2, was to measure the reflective characteristics of the engine face to incoming perturbations of pressure amplitude. This experiment will provide data to validate boundary conditions used in computational fluid dynamics (CFD) calculations.

The basic test rig from Experiment 3.1 was used as shown in Figure 2, but with the aft spacers and the wake rakes removed. A longer spacer equipped with fast actuated doors[1] was installed and a second instrumentation rake was added upstream of the doors. The door open area and the door opening and closing rate were the test variables. During transient operation of the doors, dynamic and steady state pressure measurements were recorded.

Participating Organizations Responsibilities

In general, the US side was responsible for the aerodynamic design of the test rig, the instrumentation, data acquisition systems, and test definition. The Russian side was responsible for the mechanical design, fabrication, and installation of the test rig and operation of the engine. IBP Aircraft LTD was responsible for bridging the communication barriers and bringing both sides together. The following is a list of the responsibilities for each participating organization:

General Electric
- Flowpath specification
- Instrumentation specification
- Aerodynamic/mechanical instrumentation rakes design and fabrication
- US equipment shipment coordination
- Lead for Experiment 3.2
- Test support & on-site data analysis
- Overall technical coordination

Pratt & Whitney
- Design and provide distortion screens
- Lead for Experiment 3.1
- Test support & on-site data analysis

NASA LeRC
- Aerodynamic design of flowpath
- Provide and operate fast acting doors
- Provide and operate dynamic and steady state data acquisition systems
- Overall financial/contractual coordination

Tupolev
- Flowpath mechanical design
- Flowpath hardware fabrication
- Engine and test cell preparation
- Conduct testing

IBP Aircraft LTD
- Tupolev <--> US coordination
- Translate/distribute data packages
- Interpretation and transportation services

Interfaces

The wide variety of interfaces associated with the Tu-144 engine ground experiments involved not only the obvious interface between the US and Russia (Tupolev), but also between two of the United States major aircraft engine manufacturers (General Electric and Pratt & Whitney), and NASA Lewis. These interfaces can be categorized into two major groups: Technical interfaces and Logistical interfaces.

The Technical interfaces involved identifying and resolving various technical issues associated with the design, fabrication, and testing for the experiments to be performed. For example, the aerodynamic design of the inlet systems to be evaluated was the primary responsibility of the US and was a collaborative effort between NASA Lewis and General Electric with Tupolev playing a minor role in the design. Once the aerodynamic design was completed, Tupolev had the primary responsibility for the structural design and fabrication of the inlet system with the US providing some input to the process. Several areas, such as data system requirements and responsibilities, instrumentation, Fast Acting Door (FAD) integration, and on-site computer network design and installation were similar in structure to the above interface example.

The Logistical interfaces dealt primarily with how hardware and personnel were transported and used. Some examples of areas that fall into this category are export/import requirements, hardware shipping logistics, personnel issues (team transportation coordination, visa procurement, in-country transportation), off-site communication, on-site focal points, and language interpretation and translation. All of the above examples involved multiple interfaces with both Tupolev and US team members.

Accomplishing this type of multiple interface activity domestically would have been difficult enough without adding the complexity of interfacing with a foreign company. Upon closer inspection of the entire project interface activity, two activities seem key to overall success of the management of the project: 1) The establishment of a focal point for the US and Russian teams, and 2) A liaison between the US and Russia with good communication and coordination skills. The establishment of a focal point for each side allowed a common point were all issues could be discussed and resolved. By establishing that single interface point, the US team members knew where information originated and also knew where information should be sent. Action items (both Technical and Logistical) were coordinated through these central focal points so all parties were aware of their responsibilities. The liaison allowed for that common point of communication to remain open and functioning. These two activities greatly contributed to the successful coordination of the interfaces of the Tu-144 ground tests.

Program Schedule

The actual program schedule is shown in Figure 3. There were two milestones that were critical to the success of the experiments. They were the two design review meetings held in Moscow. With all the technological advances available today for nearly instantaneous communications, i.e., faxes, electronic mail, etc., those two weeks of face to face communications were key to the success of this project. Many questions were answered and many points clarified. Minor adjustments were made to the original schedule, but the overall schedule was maintained.

Test Rig and Instrumentation

The inlet structures that were used in these experiments are shown in Figure 1 for Experiment 3.1 and Figure 2 for Experiment 3.2. The inlet structure was mounted in front of a RD-36-51A engine that was used to pull air through the inlet. It consists of a bellmouth 1355 mm (53.3 in) in diameter and 3000 mm (118.1 in) long. The bellmouth was made of 2 mm (0.079 in) thick aluminum. The transition duct increased the diameter from 1355 mm (53.3 in) at the bellmouth end to 1415 mm (55.7 in) at the centerbody duct start. It was 1350 mm (53.1 in) long and was made of 10 mm (0.039 in) thick steel. The centerbody duct was 1415 mm (55.7 in) in diameter and, like the transition duct, was also made of 10 mm (0.039 in) thick steel. The spacing ducts were of the same diameter as the centerbody duct and of the same material. Only two spacer ducts were fabricated. One 470 mm (18.5 in) long corresponding to the 1/3 De spacing and another one 945 mm (37.2 in) long (2/3 De). To get the full one diameter spacing, the 1/3 and 2/3 De spacing were joined together.

Two different converging/diverging centerbodies were used during the experiments. The "high flow" centerbody was 852 mm (33.5 in) in diameter at the throat and 6530 mm (257 in) long. This centerbody was designed for a nominal corrected flow of 250 kg/s (550 lb./s). The "low flow" centerbody was 1132 mm (44.6 in) in diameter at the throat and 6530 mm (257 in) long. This centerbody was designed for a nominal corrected flow of 140 kg/s (308 lb./s). The centerbodies were made of wood mounted on a steel tube frame. They were supported by three struts 25 mm (1 in.) in diameter at the nose and at the end by two vertical struts which were 90 mm (3.54 in) thick.

A 180° distortion screen and flow fences were installed on the struts to simulate different operating conditions. The distortion screen is shown in Figure 4. The distortion screen was made using woven stainless steel wire square mesh cloth. As shown in the Figure, the 3 x 3 x 1.6 mm (3 x 3 x 0.063 in.)mesh was laid on the 1 x 1 x 6 mm (1 x 1 x 0.120 in.) mesh and held together with safety wire and supported by the struts. The 3 x 3 x 0.063 in. notation means three wires per inch in both perpendicular directions and the wire diameter is 0.063 inches.

The flow fences were installed on both sides of the struts and were to produce a thicker strut wake more typical of that from the ramp of a bifurcated two-dimensional inlet. A schematic of the flow fences is shown in Figure 5. They were made of 12 mm (0.50 in.) thick stainless steel plate and were designed for a 60 percent open area or porosity.

During Experiment 3.2 the flow entering the engine was disturbed by opening and closing six fast actuated doors (TF-30 doors) that operated simultaneously as if controlled by a single actuation system. The doors were mounted equally spaced on the circumference of the door duct and hydraulically driven. Each door unit has 8 openings 203 mm (8 in.) tall and 25.4 mm (1 in.) wide. The total flow area was 24.8 dm^2 (384 in^2). The hydraulic system was capable of opening and closing the doors in 0.05 seconds. Figure 6 shows a photo of a fast acting door and its components. Details of its components and operation can be found in Reference 1.

Initial data runs required the doors to be fixed at different values of open area in order to determine the percent of flow ingested based on engine face pressure and shock position measurements. Door scheduling changes were accomplished between runs. The actual position history of each of the six fast actuated doors was recorded in such a manner that they were time correlated to the dynamic pressure measurements. Playback examination of the pressure and door position data from the previous test run was used in determining the door schedule for the next run.

The instrumentation installed on the test rig allowed the measurement of both steady state and dynamic pressure fluctuations. The airflow conditions at the inlet/engine interface were measured by an instrumentation rake assembly comprised of seven rake elements. Each rake element was instrumented to measure steady state and dynamic pressures at each of the seven radial positions for a total of forty nine steady state and dynamic pressure measurements. Static pressures were also measured on the circumference of the outer ring in-between the rake elements. The engine instrumentation rake assembly is shown in figure 7. Two wake rakes were mounted on rake number seven, as shown. Each wake rake element had five steady state pressure measurement locations.

The shock dynamics and related characteristics were measure by static and dynamic pressure instrumentation located along the centerbody duct outer wall. There were a total of 29 steady state pressures and 19 dynamic pressures measured on the centerbody duct outer wall. There were also six static pressures measured in the bellmouth for use in computing engine airflow. The approximate location of this pressure instrumentation is shown in Figure 8.

During Experiment 3.2 a second pressure instrumentation rake assembly was added. It was mounted upstream of the fast acting doors. This rake assembly, shown schematically in Figure 9, was used to measure the pressure waves reflecting off the engine face during the doors transient operation. This rake assembly had four rake elements with three measurement locations on each. Of the three, two were facing forward and the other faced aft. Steady state and dynamic pressures were recorded at each location. Additional steady state and dynamic pressure instrumentation was also added to the fast acting doors duct.

Data Requirements

The data requirements for the experiments are shown in Table 1. A Concurrent Computer Corporation 7500 system, was used to make all the analog transient

measurements. This VME based system was configured for 128 simultaneous sample and hold channels of data each acquiring data at the required 1000 samples per second. Additionally, each channel of data was filtered using a 132dB/Oct programmable amplifier/filter to prevent aliasing of the data. The software used this UNIX based system to allow the researchers to monitor all the data on-line. A time history of each channel could be viewed as the data was being acquired as well as a graphical representation of the shock position. Calculated parameters were also displayed on-line in a tabular format to assist the test leaders. The data acquired was buffered continuously to internal hard disks until a record command was issued. This command caused the system to save the previous 10 seconds of data to file. Off-line analysis was accomplished by playing the data back and viewing the same plots and tables available on-line and by reducing the data further in order to construct specialized plots as required. Sharing of the data with our Tupolev partners was accomplished by networking their computer with the NASA computers on site. This allowed the Tupolev engineers to also have immediate access to the data.

The second data system, a Pressure Systems Inc. 780B, was used to record all the steady state pressures on the test rig. This system, running custom software on a 486-66 Personal Computer (PC), allowed for on-line calibration which permitted the test team to calibrate the system prior to each engine run. This system was configured to acquire 160 steady state pressures, perform required calculations and update the PC display at 3 times per second. The researchers used the data on this display to set inlet / engine conditions before recording data. Once "on condition" (stabilized test conditions set), data could be recorded using the PC function keys and it would be synchronized with the dynamic data system. Analysis of the data began as soon as the data was recorded. Several NASA computers networked with the data system and the Tupolev computers, again permitting both US and Tupolev team members to both access to the data instantly and simultaneously.

Test Plan

The test plan for Experiment 3.1 is shown in Table 2. The first run in Experiment 3.1 was to assess the operation of the engine and the test rig in a "clean" configuration. Configurations 2, 3 and 4 were run to measure the effect of the flow fences on the airflow quality entering the engine as a function of distance from the inlet/engine face plane. For runs 5 through 8 the wake rakes were removed and the flow fences were replaced with a 180° distortion screen. The steady and dynamic characteristics of the airflow entering the engine were measured again as a function of distance from the inlet/engine face plane. There were no other changes to test rig other than the duct spacing, the flow fences, and distortion screen changes. The high flow centerbody was used throughout Experiment 3.1.

Table 3 shows the test plan for Experiment 3.2. Both centerbodies were used in this experiment. The throttling as well as the transient characteristics of the test rig were recorded.

Test Results

Experiment 3.1 Results

Detailed analyses of the test results were not part of this project. The results presented here have the purpose of indicating that the data acquired met the objectives of the test program. The first run determined the operating characteristics of the test rig. It was accomplished with the small diameter high-flow centerbody and without the distortion screen or the flow fences. Figure 10 shows the wall static steady state pressures plotted versus axial distance from the tip of the centerbody. The static pressures at three different axial locations along the centerbody duct, where static pressures were measured at four circumferential positions, was basically the same indicating that the flow annulus had the required concentricity and that the centerbody was properly aligned in the duct.

The position and intensity of the supersonic shock wave is shown in Figure 11. Supersonic flow is achieved when the local static to freestream total pressure ratio decreases to a value of 0.528, which corresponds to nominally 7.8 psia in Figure 11. The shockwave abruptly increases this pressure. Thus the position of the shockwave is determined by minimum pressure less than 7.8 psia followed by an abrupt pressure increase. The intensity increases as the shock Mach number increases as indicated by further reduction in the minimum pressure. Once again the data exhibited the expected characteristics for this type of test. Note that the maximum Mach number that could be obtained during this particular experiment was 1.16. This was due to the unusually high ambient temperatures during the test (summer time) which reduced engine corrected speed limits

and thus corrected flow. Subsequent test during this particular experiment were conducted without achieving supersonic flow. In the judgment of the test team this did not jeopardized the value of the data obtained nor the that of the experiment.

Figure 12 shows the corrected airflow versus corrected rotor speed characteristics of the engine during this experiment. For all practical purposes, the engine rig operating conditions did not change during the different configuration changes made in the course of this testing. To isolate the effects of the spacers on the differences in measured distortion levels it was important to test a constant corrected flow. Since corrected flow is set by corrected speed, the repeatability of the corrected flow at corrected speed is then an important indication of data quality.

Experiment 3.2 Results

Experiment 3.2 was initiated about three weeks after Experiment 3.1 was concluded. By this time the ambient temperatures had dropped and supersonic flow was obtained with both centerbodies as shown in Figure 13. This figure documents the pressure recovery versus the bellmouth Mach number for different engine speeds. The airflow choked, as indicated by the constant bellmouth Mach number, at an engine corrected speed of 4167 rpm for the large diameter centerbody and 4976 rpm for the small diameter centerbody.

The throttling characteristics of the small diameter centerbody are shown in Figure 14. At shock Mach numbers of nominally 1.23 or less, the boundary layer could sustain the required pressure rise through a single shock. At Mach numbers nominally greater than 1.23, additional shocks (shock "train") were required to achieve the complete pressure rise. In spite of the lack of any boundary layer bleed, the upstream characteristics of the shock train had excellent repeatability out to the maximum supercritical condition of nominally 9%.

Duct wall root mean square (RMS) fluctuating pressure level increases were consistent with wall steady state data in documenting the shock train characteristics as shown in Figure 15. A shockwave/boundary layer interaction creates high local turbulence levels, thus "spikes" in the fluctuation pressure distribution data can be used to locate the position of the shock system and possibly determine the number of interactions by the number of such pressure spikes. The turbulence levels measured also indicate that the centerbody diffuser design was able to maintain the boundary layer attached without boundary layer bleed. The test rig was designed without bleed to simplify the design, and reduce the cost and the complexity of operating the test rig.

Data over the complete range of supercritical to unchoked operation indicated that opening the six fast acting doors had minimal impact on the circumferential distortion patterns. As shown in Figure 16 the shock train characteristics exhibited excellent repeatability. For weak shocks a single interaction with the boundary layer occurs and thus the pressure rise is monatonic. As the required shock pressure rise increases, the boundary layer locally separates at a lower pressure rise, resulting in a number of smaller sequential shock interactions (or shock "train") to achieve the required overall pressure rise. The door transient times were on the order of ten times faster than the times measured for completion of the induced pressure change.

At some conditions, opening the fast acting doors resulted in transient propagation of the leading edge of the shock system to a position upstream of its subsequent steady state location. This is shown in Figure 17. At certain operating conditions, bi-stable shock system operation was also observed and transiently measured (consistent with on-line steady state pressure distribution observations).

At the conclusion of the small diameter centerbody testing, the test rig was re-configured with the large diameter, low flow, centerbody installed. Upon resumption of testing, the circumferential steady state static pressures, as shown in Figure 18, again indicated excellent alignment and flow symmetry. A larger range of supercritical operation than with the small diameter centerbody was achieved before encountering significant shock train phenomena as shown in Figure 19. The degree of supercritical operation is related to the terminal shock system Mach number which in turn is related to the minimum wall static pressure. Lower static pressures with monatonic pressure rise thus indicate a higher degree of supercritical operation before a shock train was required in achieving the required overall pressure rise. Figure 20 illustrates that the RMS levels for the large diameter centerbody were again consistent with wall steady state data in documenting the shock train characteristics. The peaks in the measured turbulence levels correspond

well with the non-monatomic steady-state pressure distribution, thus confirming the location and "footprint" of the shock system between the two data types. The turbulence levels measured also indicate that the centerbody diffuser design was able to maintain attached the boundary layer without boundary layer bleed.

Like with the small diameter centerbody, the shock train characteristics once again exhibited excellent repeatability during the opening of the doors as shown in Figure 21. In contrast, however, data obtained with the large diameter centerbody did not exhibit significant transient propagation of the leading edge of the shock system to a position upstream of its subsequent steady state location as observed with the small diameter centerbody.

The repeatability of the data and the previously discussed observations are considered testimony to the high quality of the test data produced from these experiments by the international team working together.

Summary

The Tu-144 Engine Ground Tests were completed in Moscow, Russia. The data obtained will be instrumental in the design of safe and efficient inlet systems for future high-speed civil transports. All the objectives set forth at the beginning of the project were met and was the result of excellent teamwork between all the parties involved. The team was able to maintain the schedule to control the costs of the project without sacrificing the scope or the schedule.

This project presented many technical and cultural challenges. The very nature of our historical and political differences were an obvious disparity, yet this joint effort was an outstanding success.

Acknowledgments

The key to the success of this joint US/Russia project sponsored by NASA in support of the HSR Program was talented individuals working together as a team. The US side was represented by engineers and technicians from the NASA Lewis Research Center, General Electric Aircraft Engines, and Pratt & Whitney. The Russians were represented by engineers and technicians from the Tupolev Design Bureau and the Rybinsk Engine Design Bureau. A vital contributor was IBP Aircraft LTD who provided expert translation and interpretative services that brought the two sides together. We want to recognize the excellent contributions of the following individuals:

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Mr. Michail Melnichenko

General Electric:
Mr. William Albertson
Mr. Pete Kutschenreuter

Pratt & Whitney:
Mr. Michael Kirby
Mr. Frank Thompson
Mr. Mark Welsh

References

1. J. A. Webb, Jr., O. Mehmed, and K. W. Hiller, "Improved Design of a High-response Slotted-plate Overboard Bypass Valve for Supersonic Inlets," NASA TM X-2812, June 1973.

	Dynamic Data System Requirements:	Steady State Data System Requirements
Aprox. # of parameters	128 parameters	160 parameters
Types of parameters	Pressures (Kulites), engine speeds, temperatures, strain gages, TF-30 door actuation.	Pressures
Sampling rate	1000 - 2000 samples per second	N/A
Playback capability	On-line as well as off-line	On-line as well as off-line
Graphics capability	On-line display	
Data archival	Data storage to media	Data storage to media
Power required	Compatible with 240 VAC/ 50 Hz power	Compatible with 240 VAC/ 50 Hz power
Operating environment	Moderately uncontrolled temperature environment	Moderately uncontrolled temperature environment

Table 1. Data requirements for Experiments 3.1 and 3.2.

Configuration	Spacing	Comments	Test #	Date Completed
#1 Clean Inlet	1 De	(No Flow Fences)	1 & 2	14 - 8 - 96
#2 Flow Fences	1 De		3	16 - 8 - 96
#3 Flow Fences	1/3 De		4	20 - 8 - 96
#4 Flow Fences	0 De		5	23 - 8 - 96
#5 180° Dist. Screen	1 De	(No Flow Fences)	6	26 - 8 - 96
#6 180° Dist. Screen	1/3 De	(No Flow Fences)	7	29 - 8 - 96
#7 180° Dist. Screen	0 De	(No Flow Fences)	8	02 - 9 - 96
#8 180° Dist. Screen	2/3 De	(No Flow Fences)	9	05 - 9 - 96

Table 2. Test plan for Experiment 3.1.

Test #	Engine Parameters			Door Position (% Open)	Comments
	% RPM	Corrected Speed (RPM)	Airflow (Kg/s)		
1	Small Centerbody 9/30/96; T_{amb}=12.8 °C; P_{atm}= 1.033 kg/cm^2				
	85	4820	224	0-50	Door calibration
	85	4820	224	0-50	..
	88	4976	241	0	Throttling characteristic
	90	5148	253	0	Throttling characteristic
	91	5212	260	0	Throttling characteristic
	92	5246	265	0	Throttling characteristic
	93	5294	271	0	Throttling characteristic
	94	5346	274	0	Throttling characteristic
	89	5090	251	0	Throttling characteristic
2	Small Centerbody 10/3/96; T_{amb}= 17.8 °C; P_{atm}= 1.015 kg/cm^2				
	85.5	5000	226	0	Check point
	91.5	5170	258	0-10-20-0	Doors operation
	91.5	5170	258	16-0	Doors operation
	93.5	5280	269	0-20-0-40	Doors operation
	93.5	5280	269	0-30-0-50-0	Doors operation
3	Large Centerbody 10/14/96; T_{amb}= 11.1 °C; P_{atm}= 1.027 kg/cm^2				
	67	3842	114	0	Throttling characteristic
	68.5	3965	126	0	Throttling characteristic
	70.5	4060	136	0	Throttling characteristic
	72	4167	148	0	Throttling characteristic
	73.7	4196	156	0	Throttling characteristic
	74.5	4241	159	0	Throttling characteristic
	74.5	4296	160	0-30-0	Doors operation
4	Large Centerbody 10/15/96; T_{amb}= 10.0 °C; P_{atm}= 1.029 kg/cm^2				
	72.5	4132	146	0	Check point
	73.5	4235	155	0-10-0-20	Doors operation
	73.5	4235	155	0-30-0-40	Doors operation
	73.5	4235	155	0-50-0-60	Doors operation
	73.5	4235	155	0	Doors operation
	74.5	4300	161	0-20-0-40	Doors operation
	74.5	4300	161	0-50-0-60	Doors operation
	74.5	4300	161	0-75-0	Doors operation

Table 3. Test plan for Experiment 3.2.

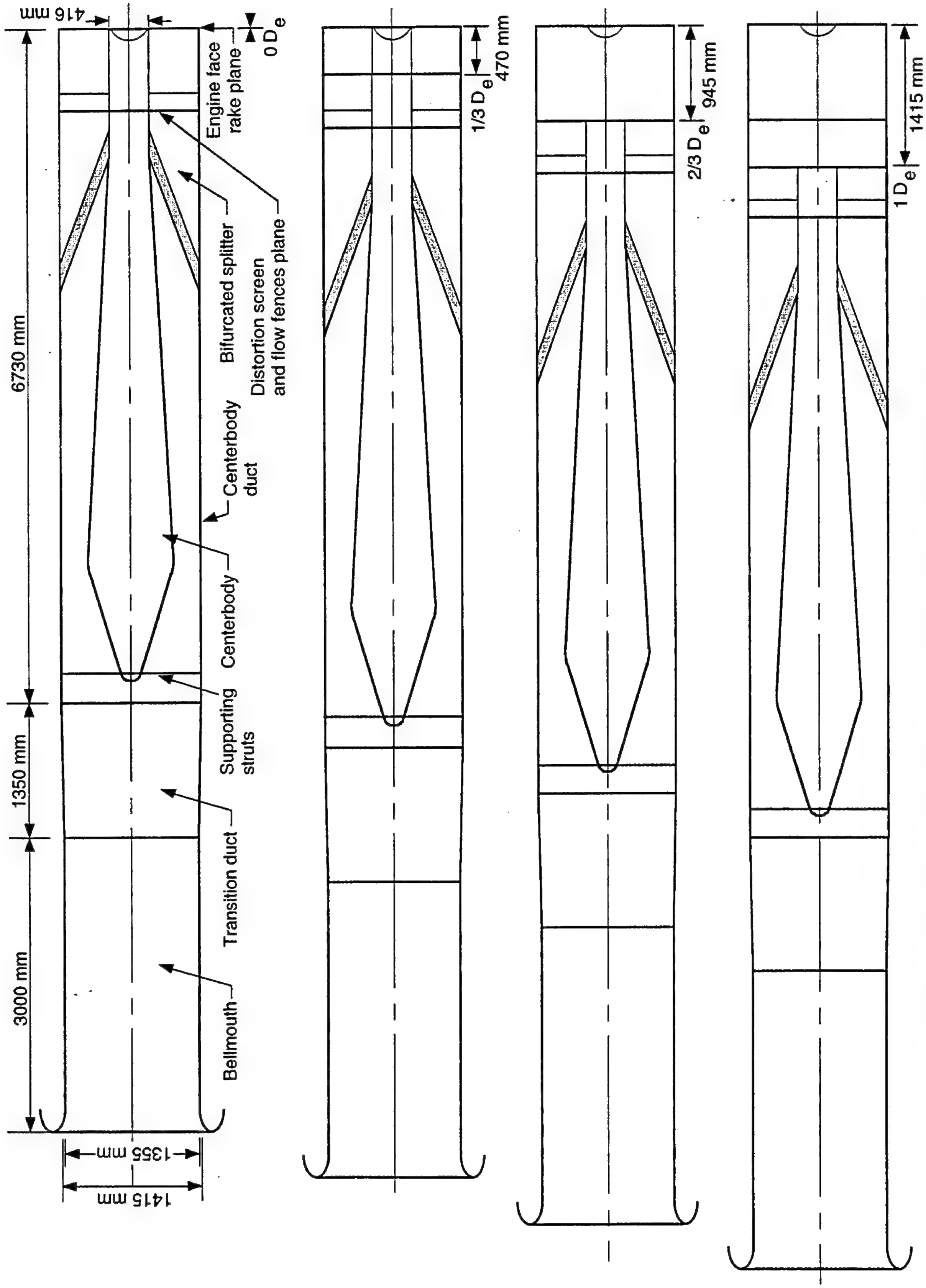

Figure 1.—Schematic of Experiment 3.1 test showing spacer configurations. (Not to scale.)

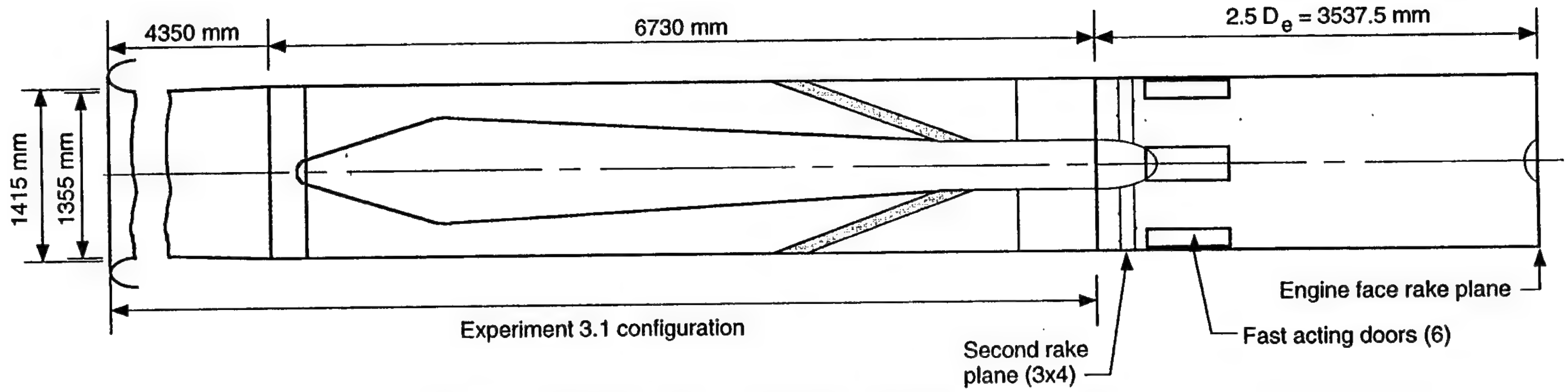

Figure 2.—Schematic view of Experiment 3.2 set-up. (Not to scale.)

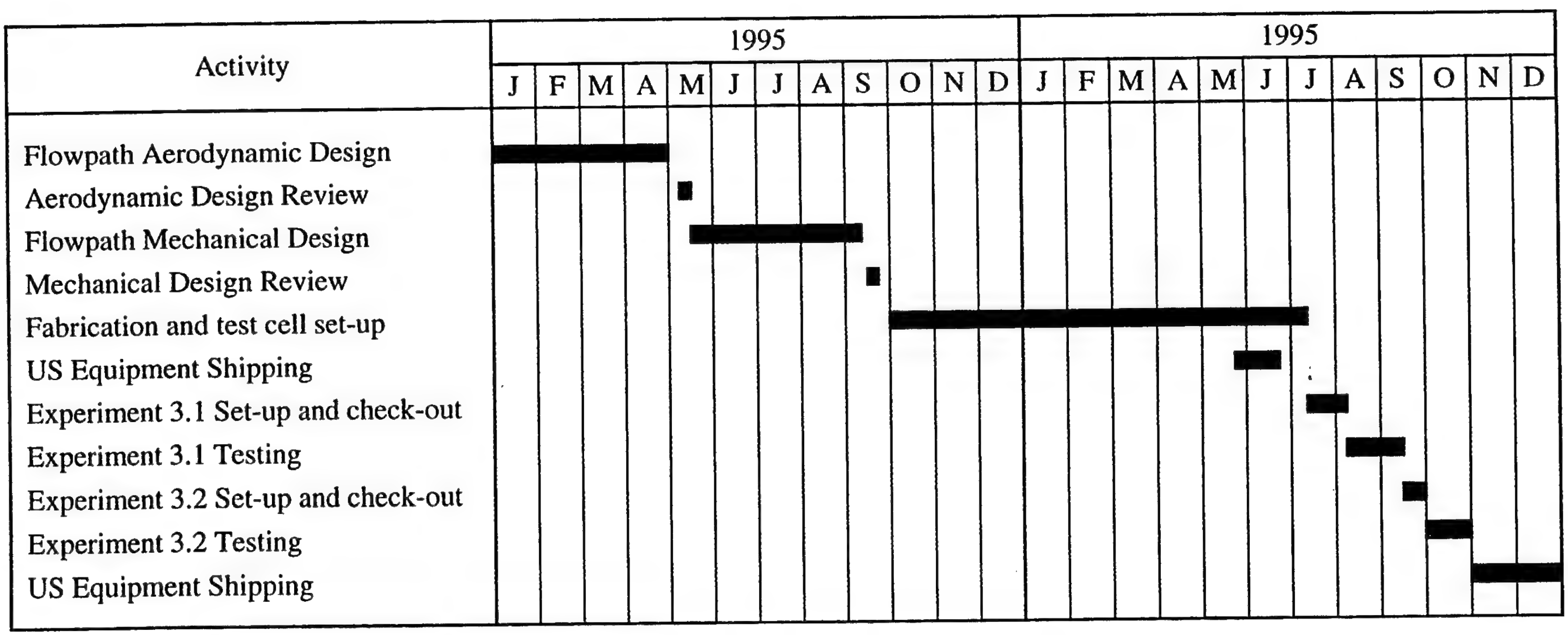

Figure 3.—Tu-144 Engine Ground Tests schedule.

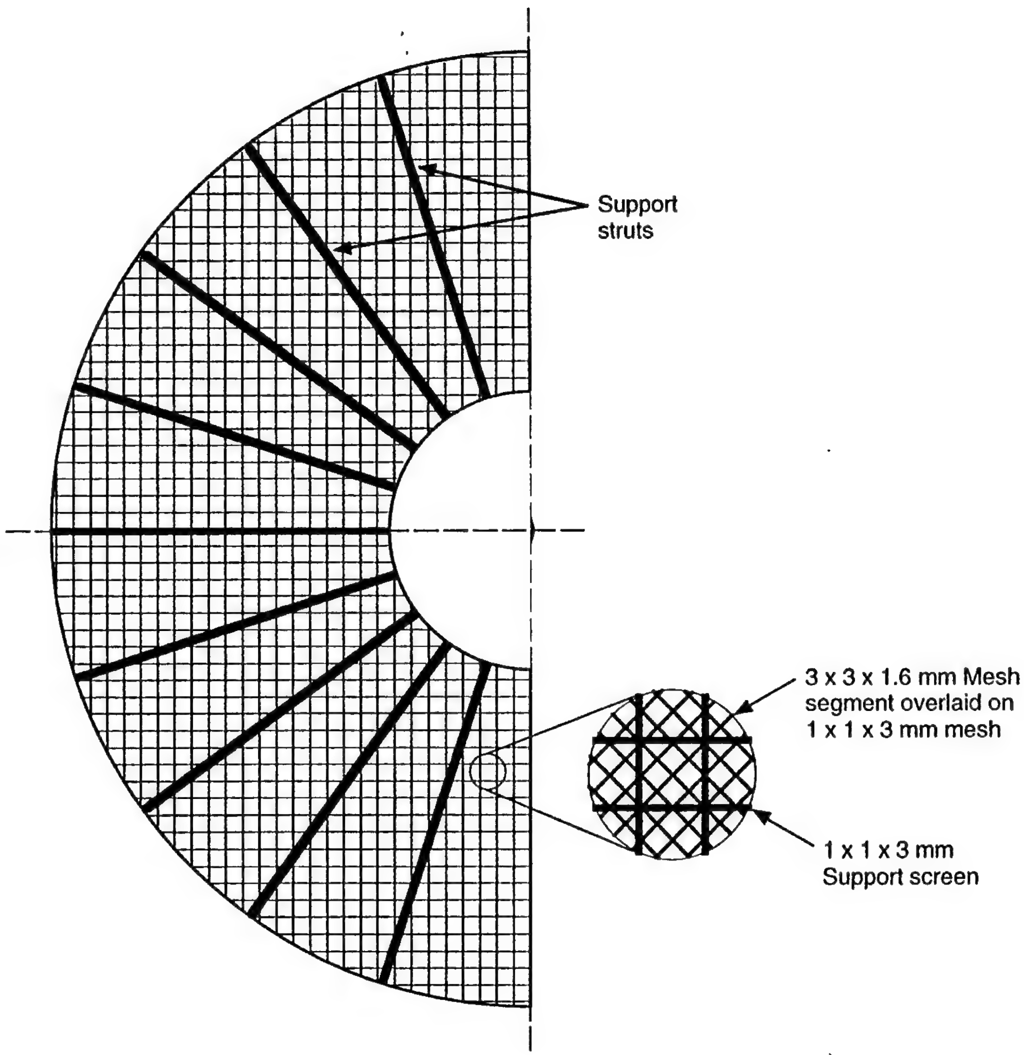

Figure 4.—Schematic of distortion screen used in Experiment 3.1. Forward looking aft.

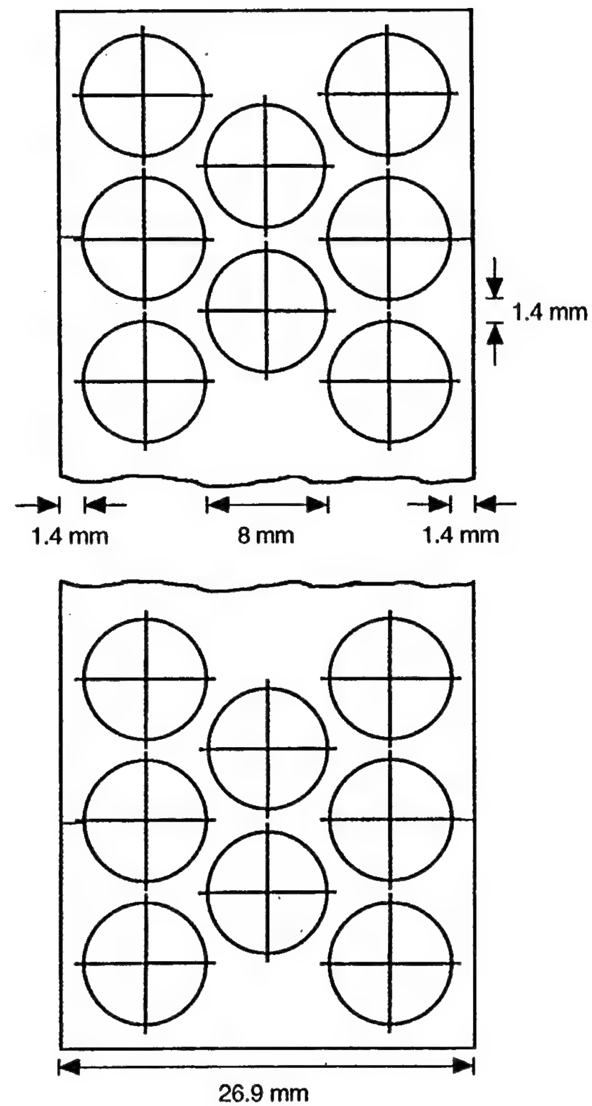

Figure 5.—Schematic of flow fences used in Experiment 3.1.

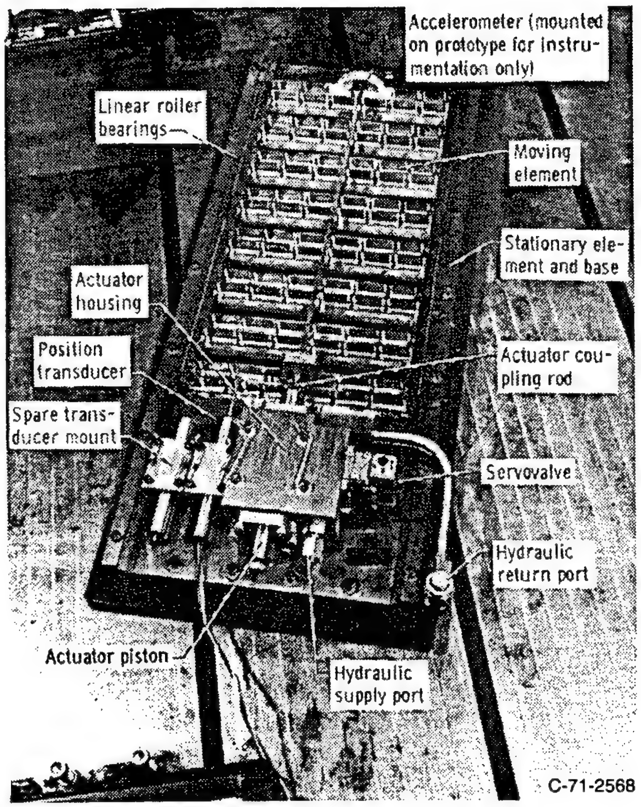

Figure 6.—Improved overboard bypass valve for supersonic inlets.

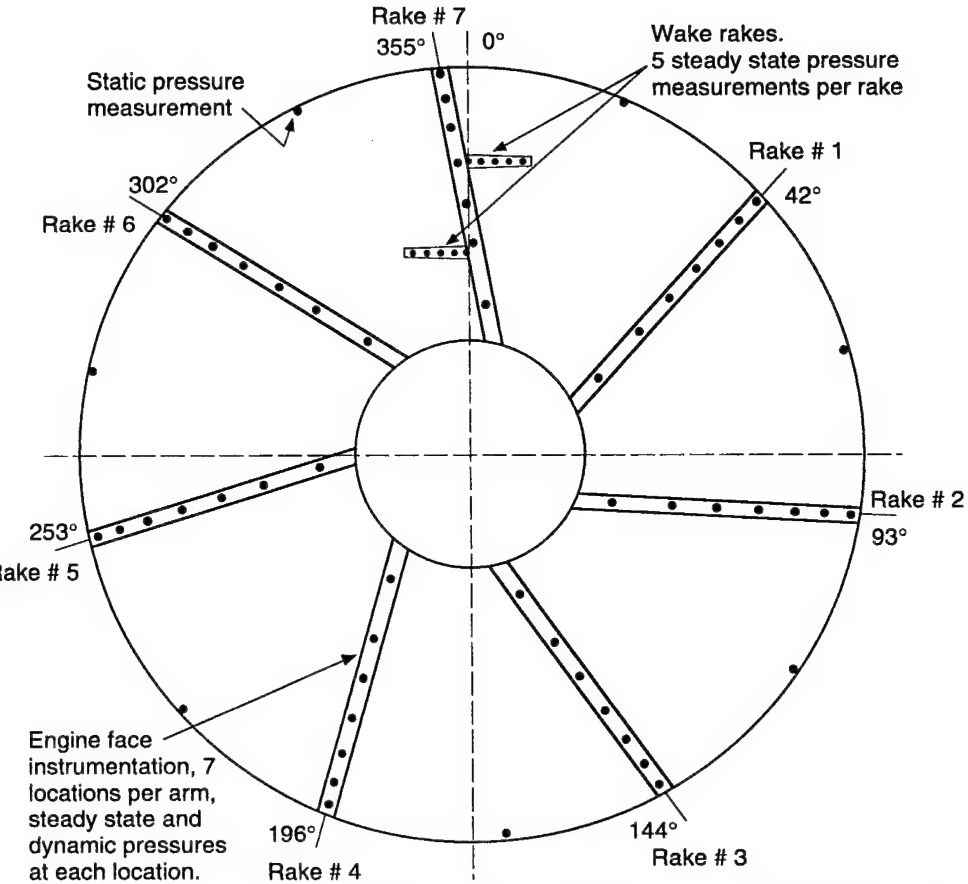

Figure 7.—Schematic of inlet/engine interface instrumentatiom rake. Forward looking aft.

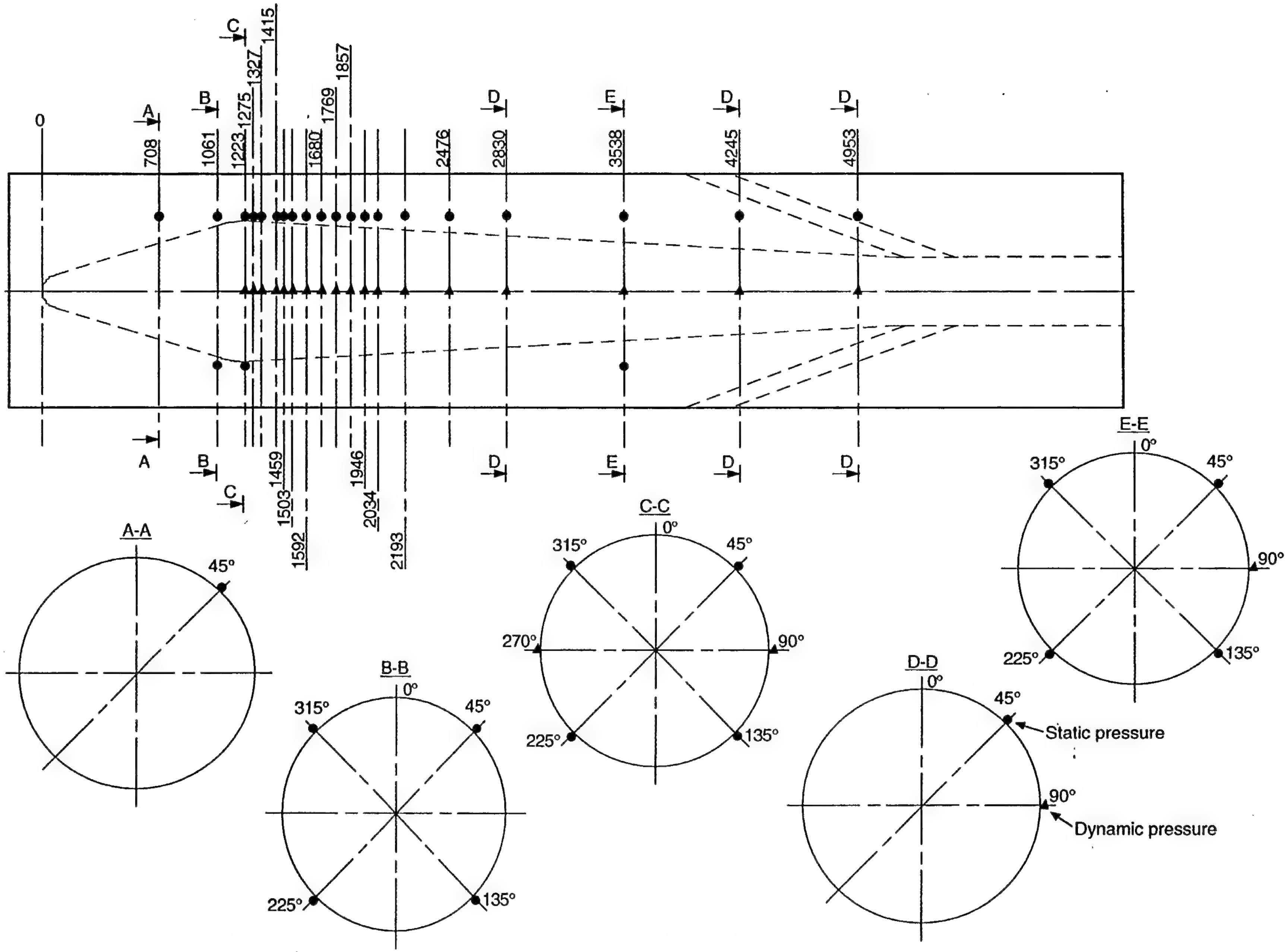

Figure 8.—Approximate location of pressure measurements on the duct centerbody. All dimensions in mm. (Not to scale.)

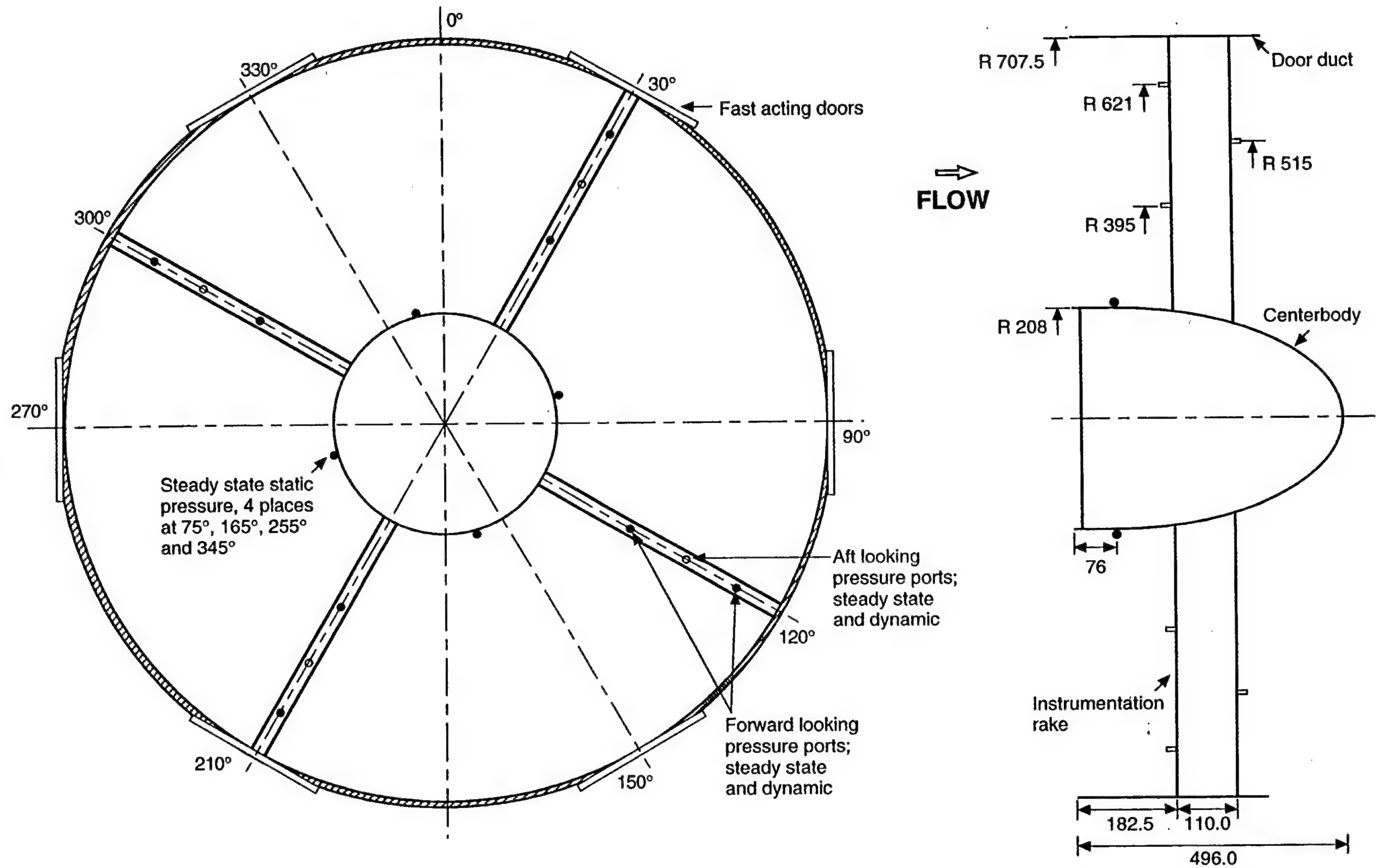

Figure 9.—Schematic of 3x4 instrumentatiom rake use in Experiment 3.2. All dimensions in mm. Forward looking aft. (Not to scale.)

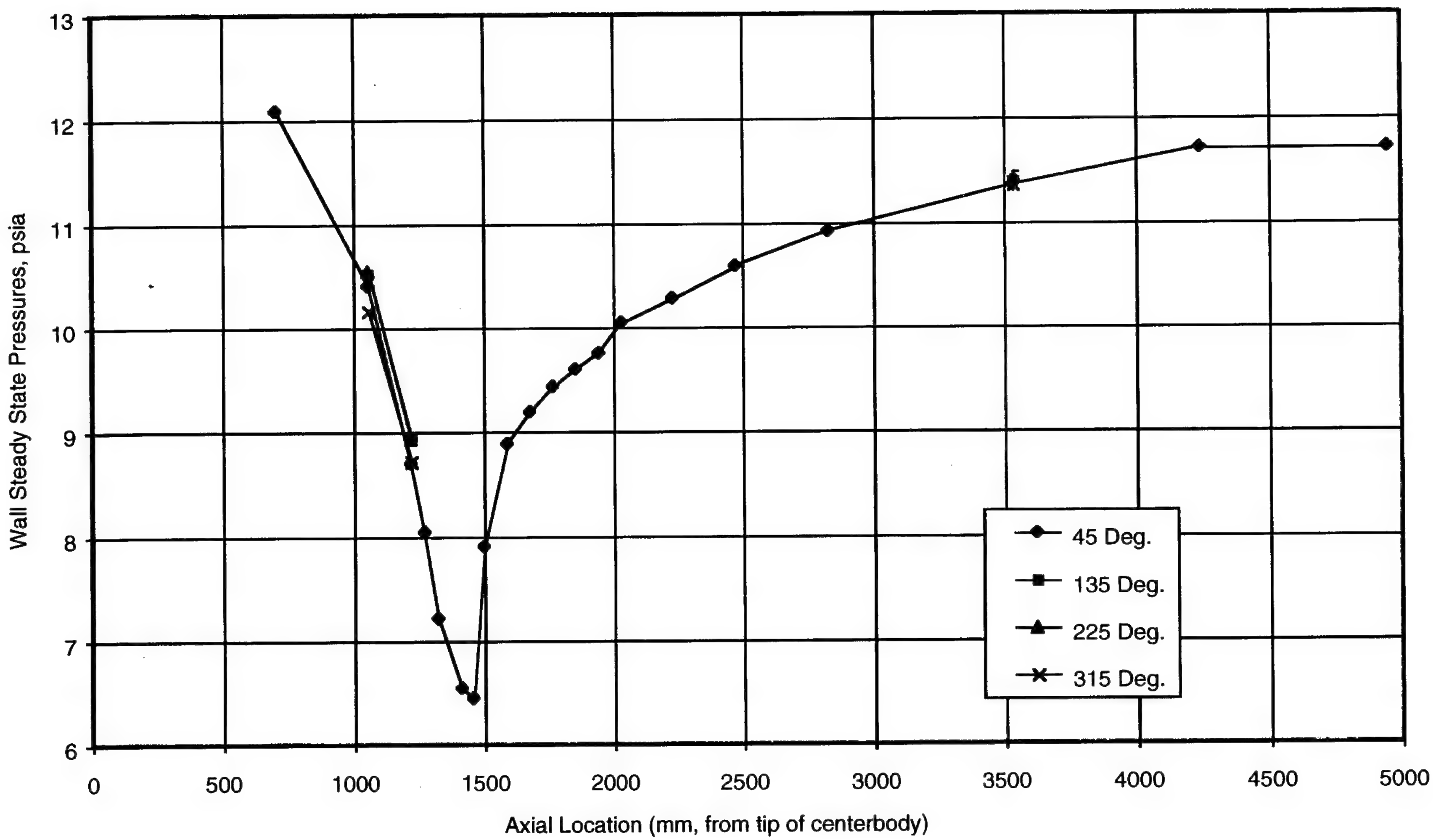

Figure 10.—Axial steady state pressure profile for small diameter centerbody, corrected engine speed 5100 rpm. Pressure circumferential locations are clockwise from the top, forward looking aft.

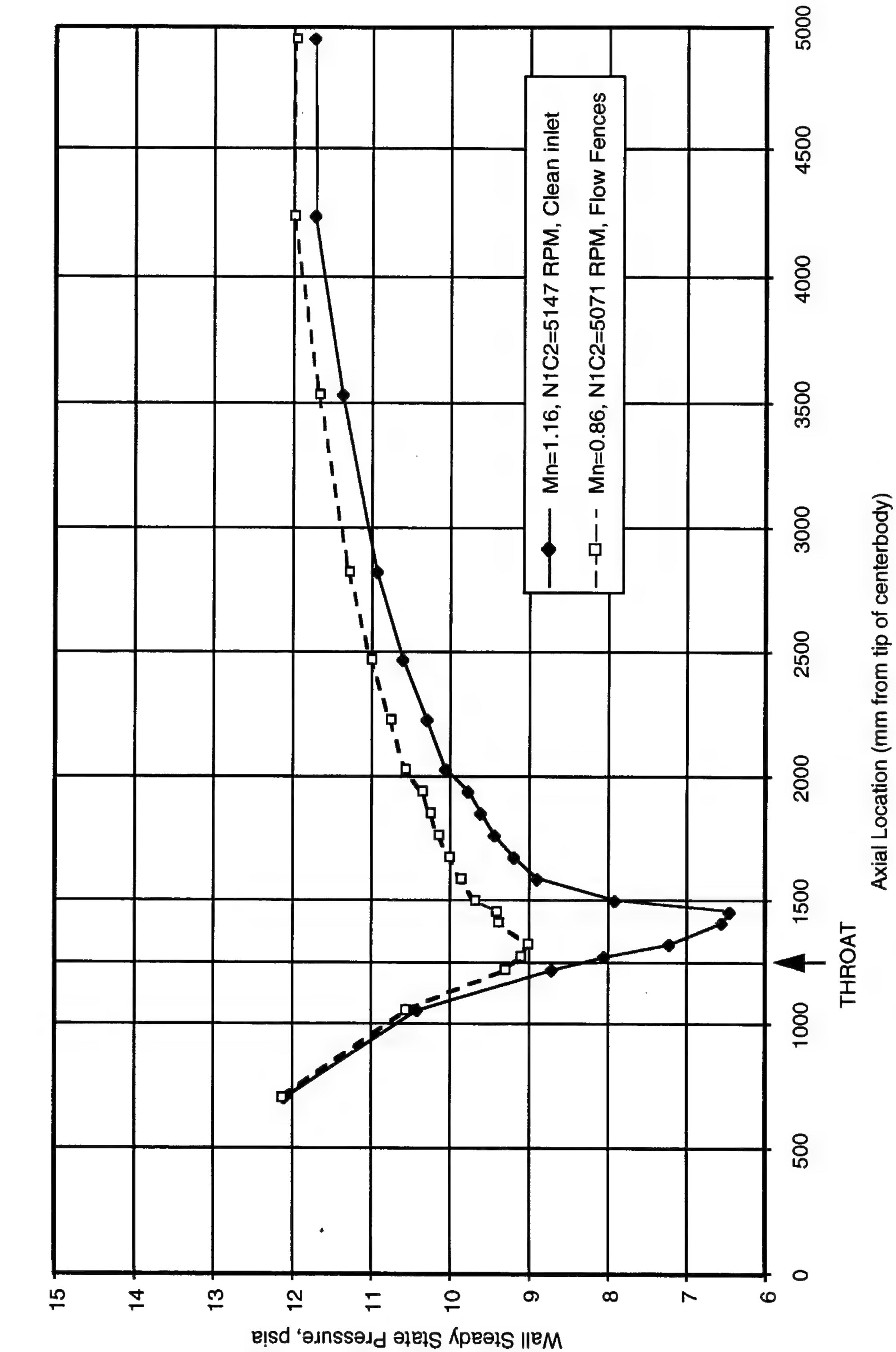

Figure 11.—Position and intensity of shock wave during Experiment 3.1.

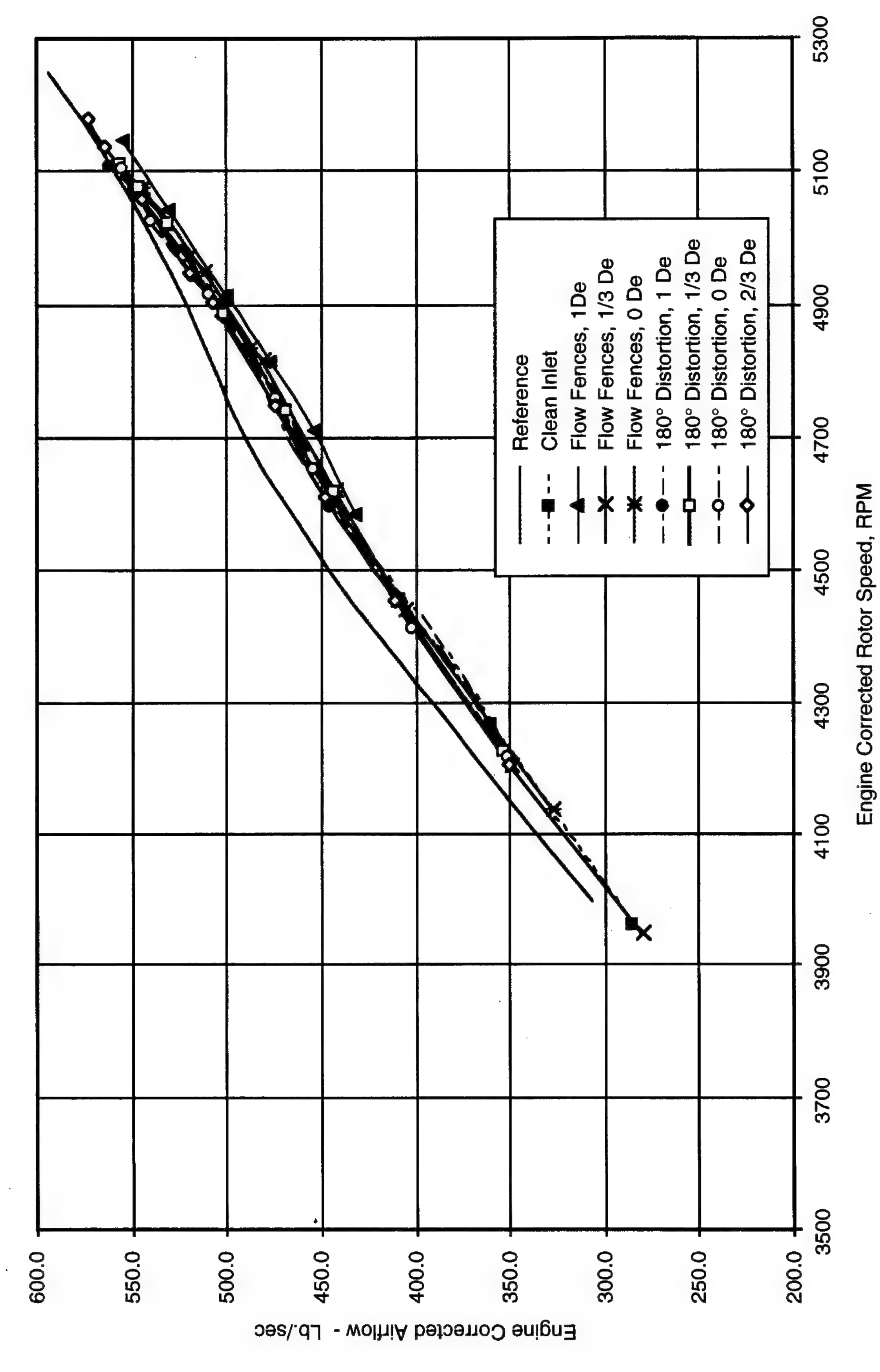

Figure 12.—Engine corrected airflow versus corrected rotor speed characteristics for Experiment 3.1.

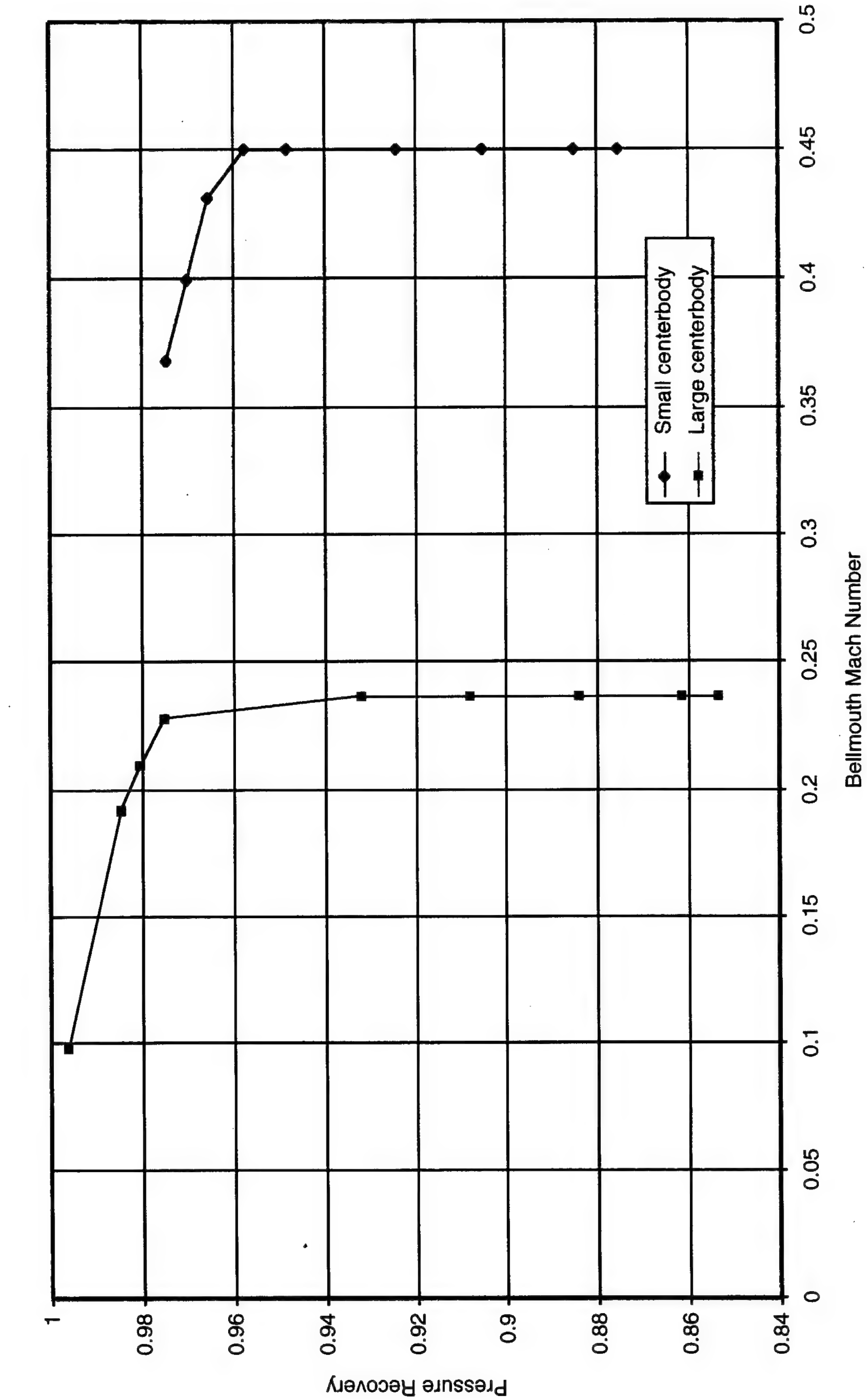

Figure 13.—Bellmouth Mach number as a function of inlet pressure recovery.

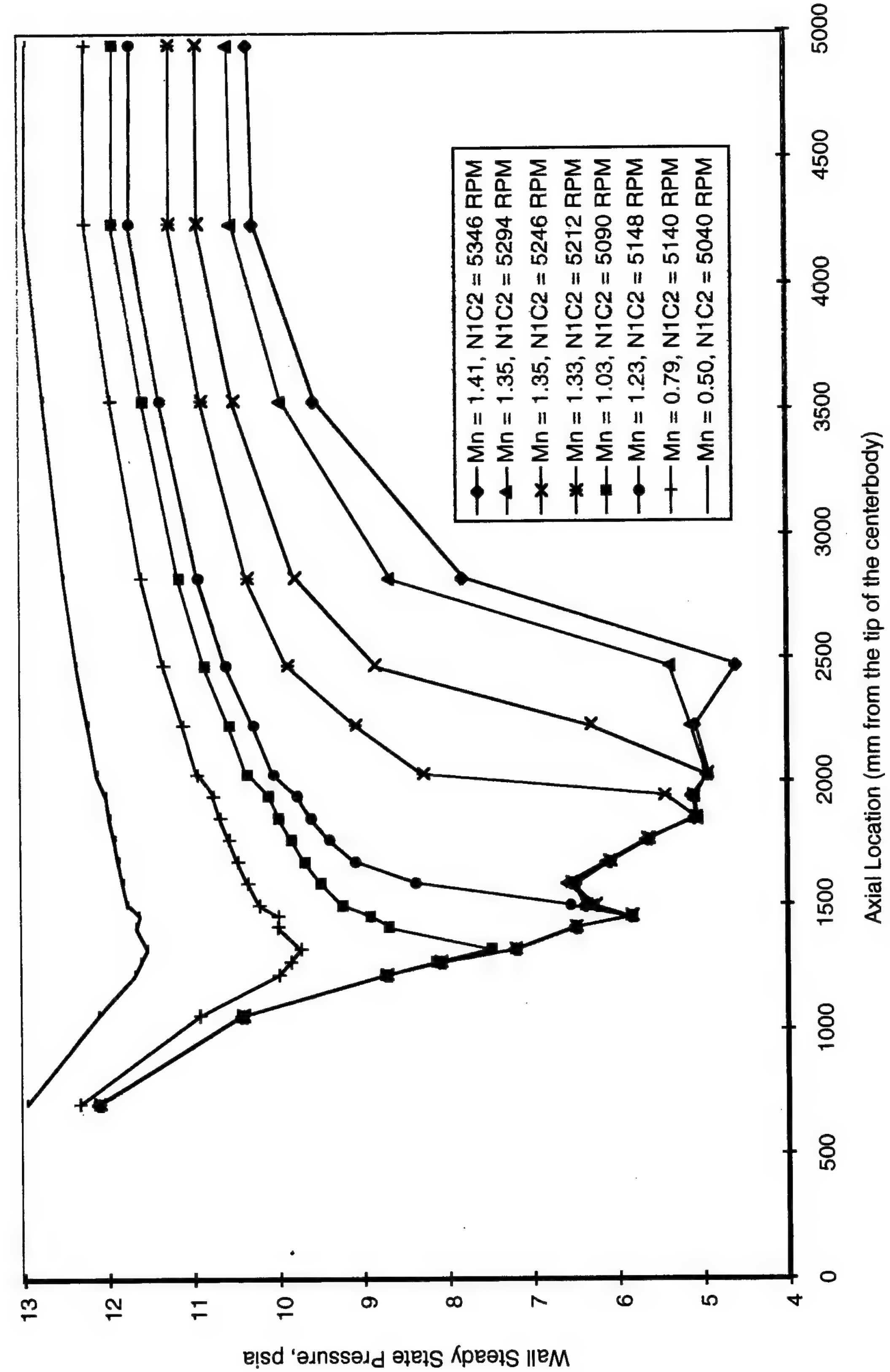

Figure 14.—Throttling characteristics of the small diameter centerbody.

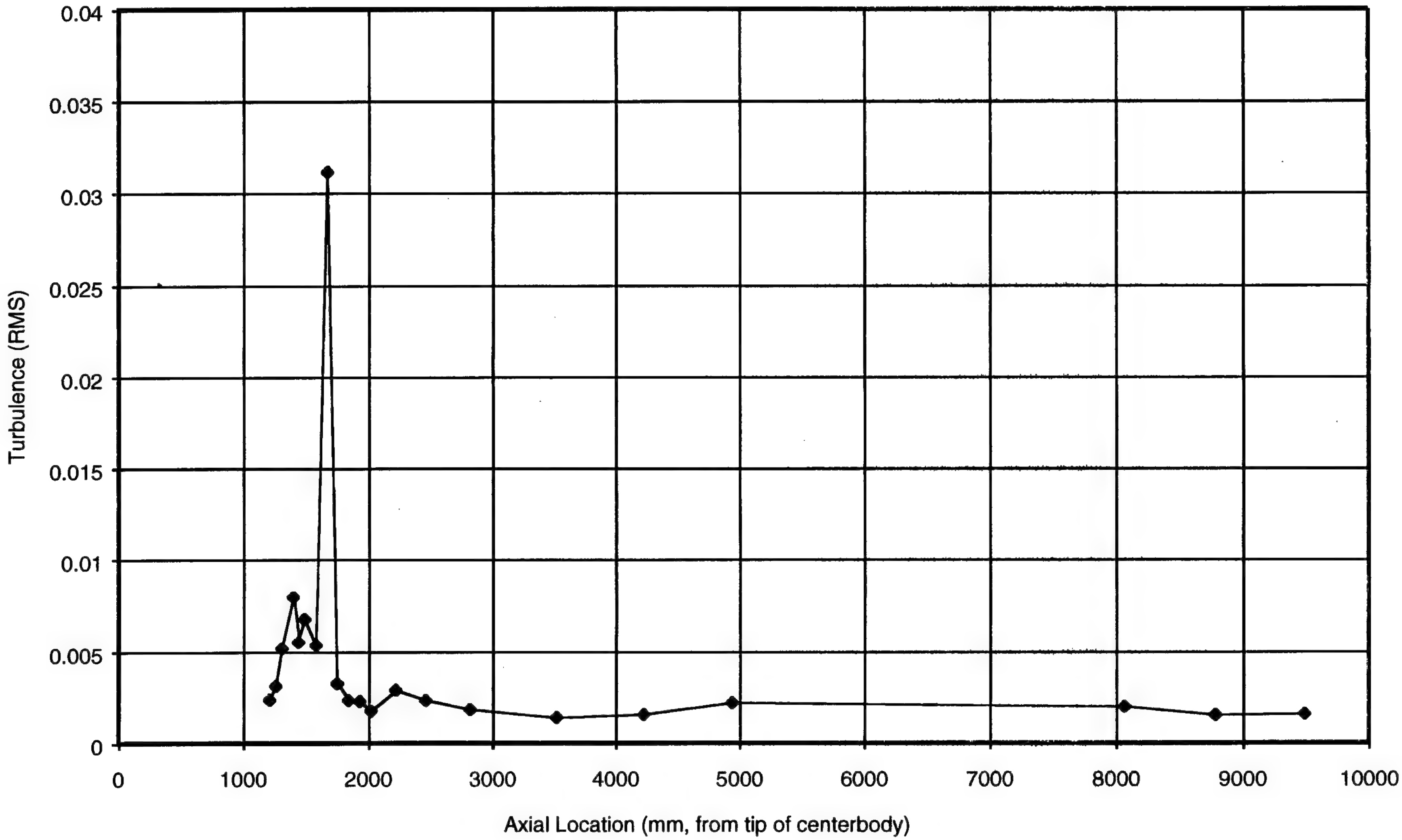

Figure 15.—Duct wall root mean square fluctuating pressure levels for the small diameter centerbody, Mach number = 1.07, engine corrected speed = 5170 RPM.

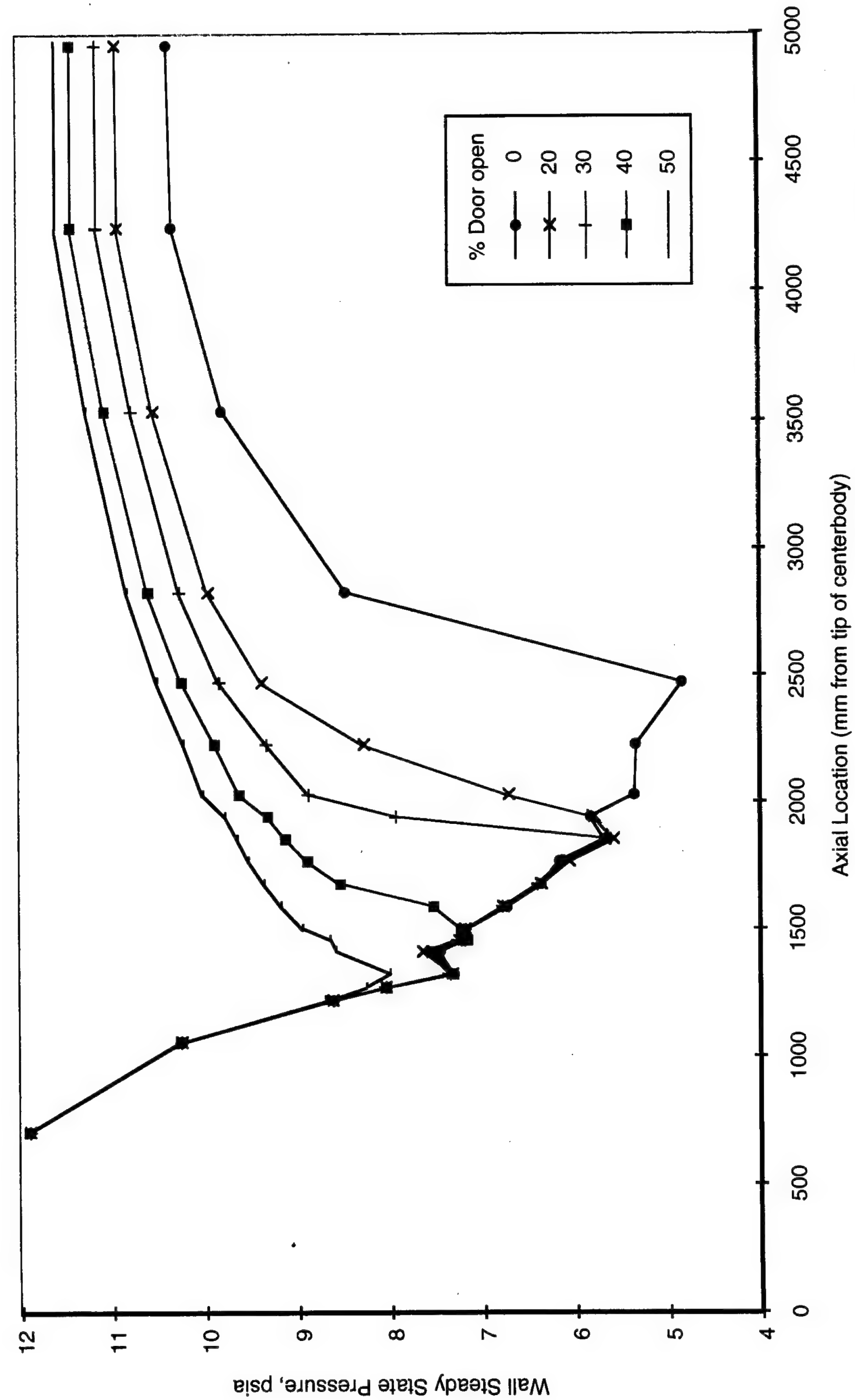

Figure 16.—Shock position for the small diameter centerbody for various door open positions at an engine corrected speed of 5280 RPM.

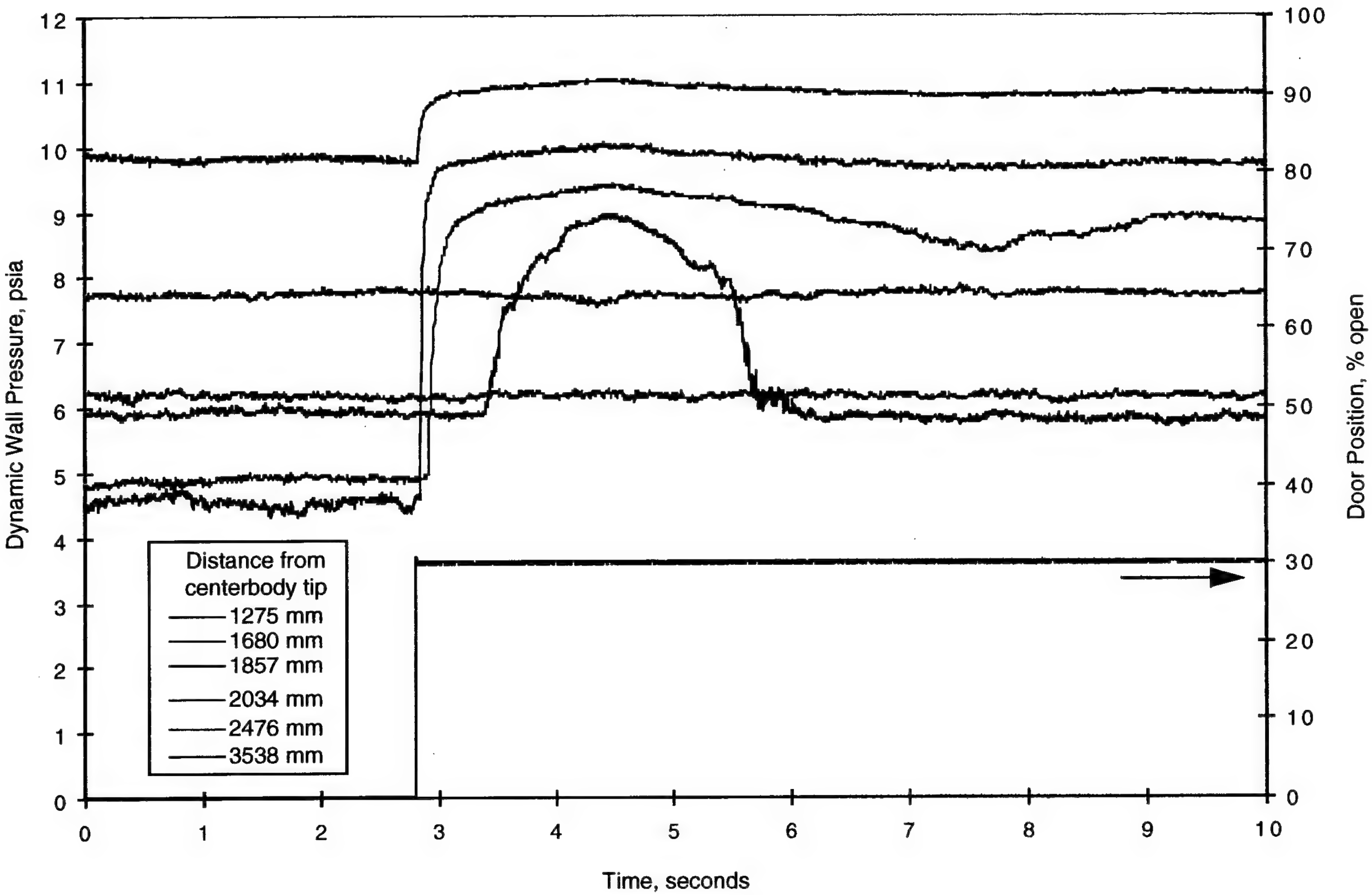

Figure 17.—Transient shock propagation for the small diameter centerbody at an engine corrected speed of 5185 RPM.

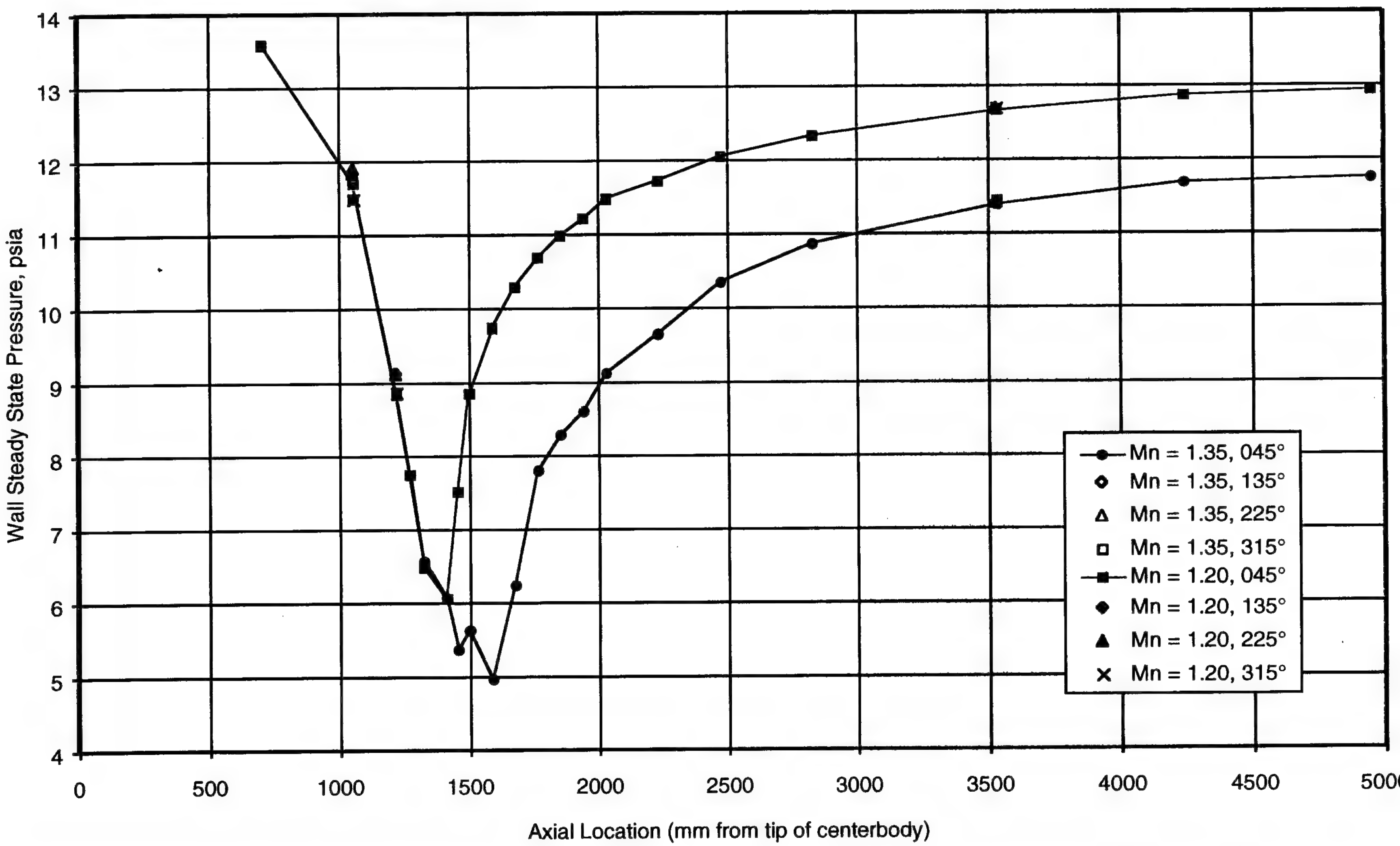

Figure 18.—Axial steady state pressure profile for large diameter centerbody. Pressure circumferential locations are clockwise from the top, forward looking aft.

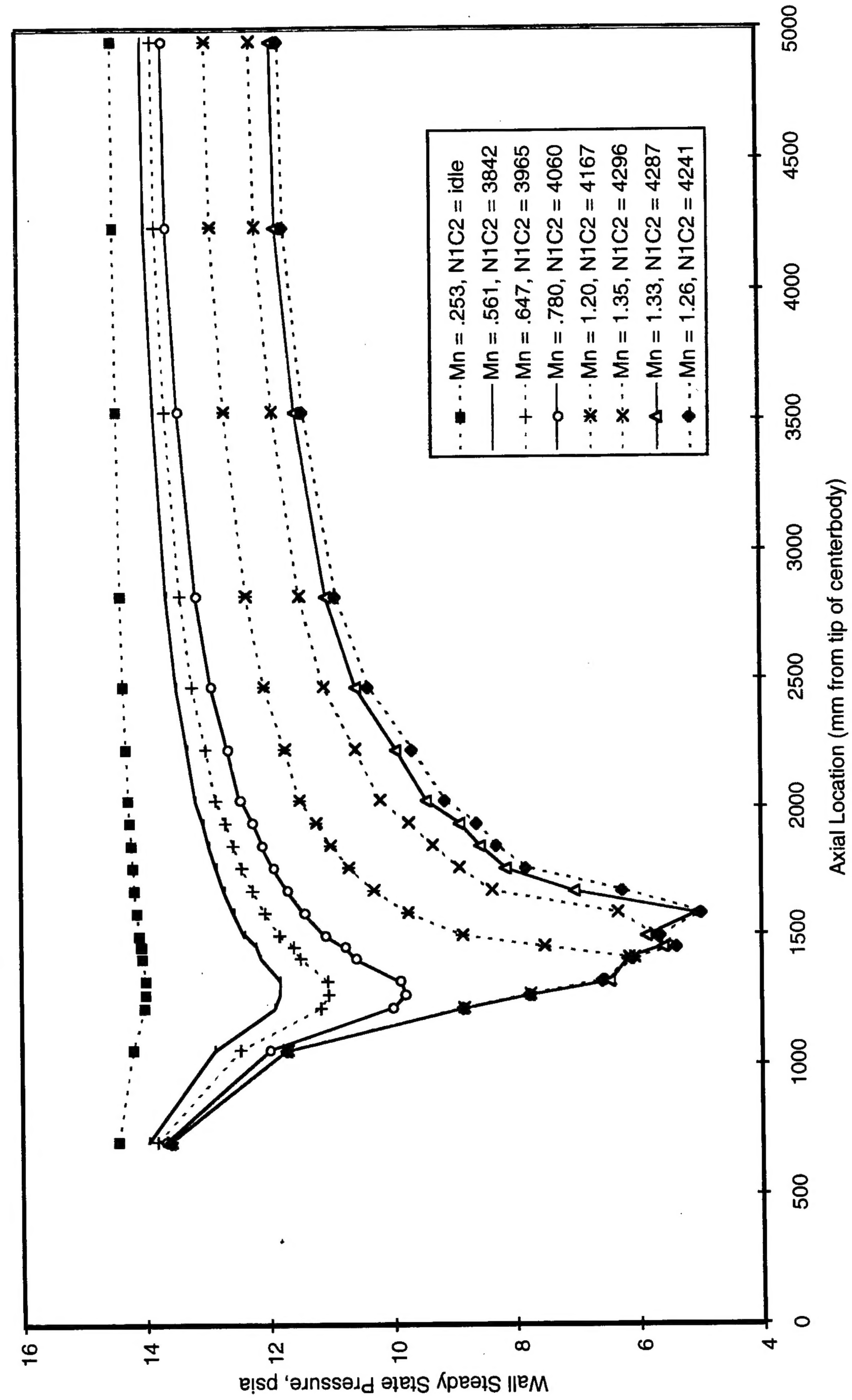

Figure 19.—Throttling characteristics of the large diameter centerbody.

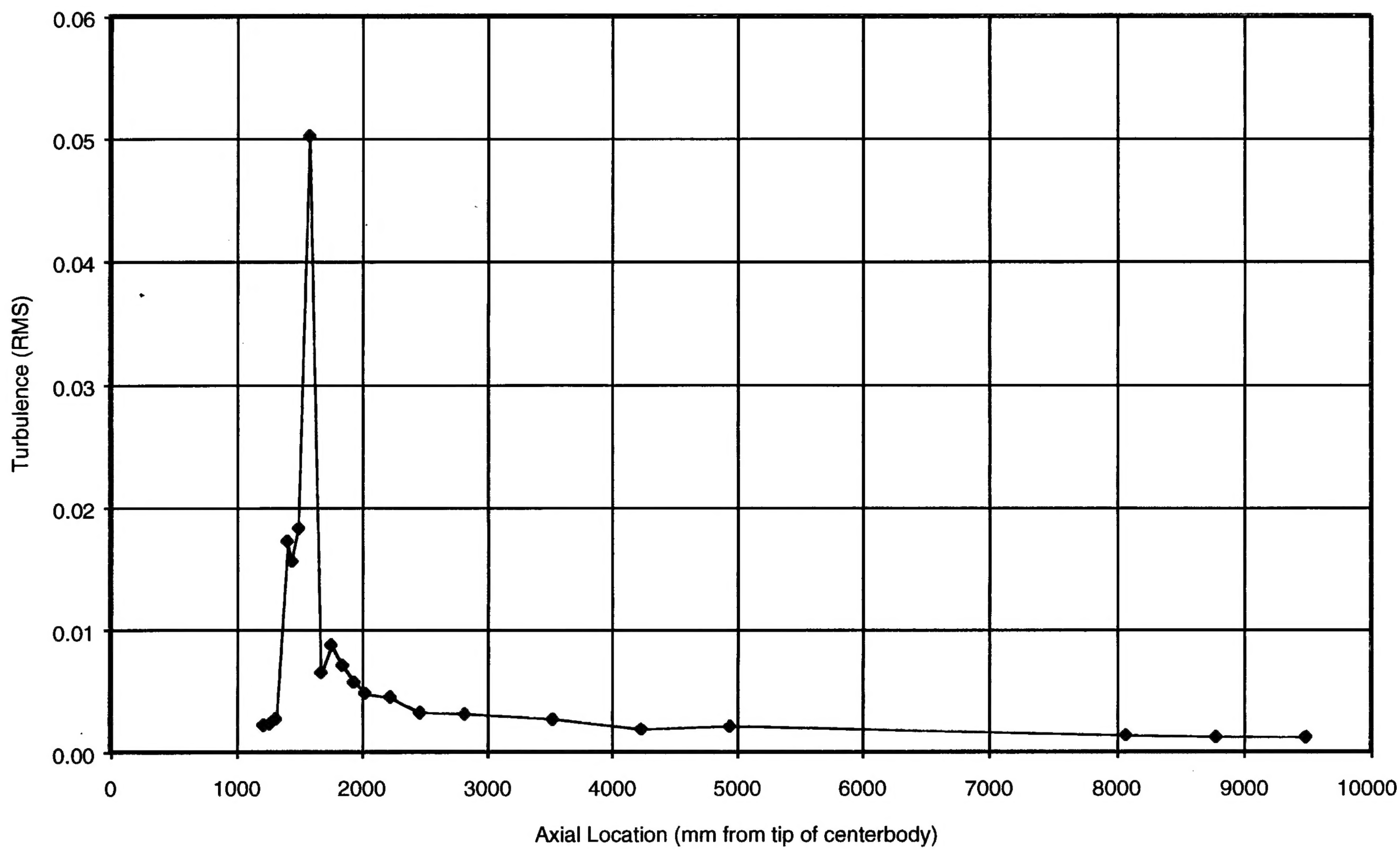

Figure 20.—Duct wall root mean square fluctuating pressure levels for the small diameter centerbody, Mach number = 1.31, engine corrected speed = 4273 RPM.

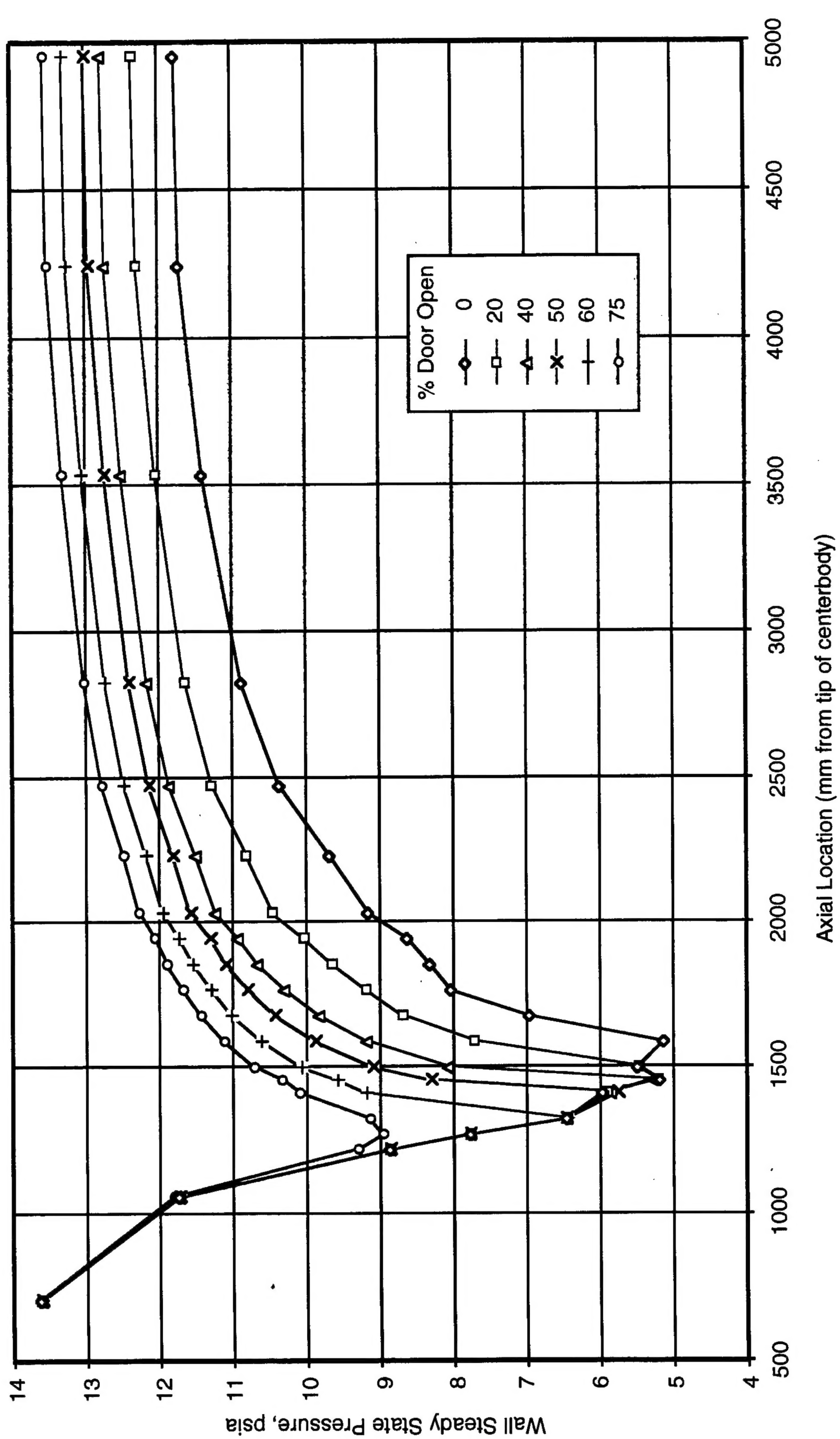

Figure 21.—Shock position for the large diameter centerbody for various door open positions at an engine corrected speed of 4300 RPM.

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13. ABSTRACT *(Maximum 200 words)*

Two engine research experiments were recently completed in Moscow, Russia using an engine from the Tu-144 supersonic transport airplane. This was a joint project between the United States and Russia. Personnel from the NASA Lewis Research Center, General Electric Aircraft Engines, Pratt & Whitney, the Tupolev Design Bureau, and IBP Aircraft LTD worked together as a team to overcome the many technical and cultural challenges. The objective was to obtain large scale inlet data that could be used in the development of a supersonic inlet system for a future High Speed Civil Transport (HSCT). The first experiment studied the impact of typical inlet structures that have trailing edges in close proximity to the inlet/engine interface plane on the flow characteristics at that plane The inlet structure simulated the subsonic diffuser of a supersonic inlet using a bifurcated splitter design. The centerbody maximum diameter was designed to permit choking and slightly supercritical operation. The second experiment measured the reflective characteristics of the engine face to incoming perturbations of pressure amplitude. The basic test rig from the first experiment was used with a longer spacer equipped with fast actuated doors. All the objectives set forth at the beginning of the project were met.

14. SUBJECT TERMS

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